

# DC and RF Performance of AlGaIn/GaN HEMTs on SiC at High Temperatures

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## Introduction

GaN-based transistors have demonstrated to be the most promising candidates for applications with high power and high frequency requirements, and working in harsh environments. They take advantage of some interesting properties of nitrides such as their thermal stability or high electron velocity, together with a high sheet carrier density ( $\sim 10^{13} \text{ cm}^{-2}$ ) provided by AlGaIn/GaN heterostructures thanks to the favorable band offsets and internal piezoelectric fields. In above applications, transistors may work in small signal amplifiers under high ambient temperatures, or in power amplifiers where channel temperatures may increase significantly. Thus, high temperature (HT) operation and related reliability issues have become important research topics in GaN electronics. Although some works have been recently published about DC characterization of HEMTs at HT [1-5], there are few papers studying their behaviour at RF [4,5]. This work aims to understand the small signal performance of AlGaIn/GaN HEMTs on SiC at HT, using DC and RF measurements combined with proper modeling and small signal parameters extraction.

## Experimental

Al<sub>0.28</sub>GaN<sub>0.72</sub>/GaN HEMTs, with 25 nm barriers, were grown on SiC by metal-organic chemical vapour deposition. The sheet carrier density was  $9.9 \cdot 10^{12} \text{ cm}^{-2}$ . Ti/Al/Pt/Au metallizations were used for ohmic contacts, obtaining contact resistances of  $0.15 \text{ } \Omega \cdot \text{mm}$  and sheet resistances of  $\sim 475 \text{ } \Omega/\square$ . Ni/Au was used for the Schottky T-shape gates,  $0.25 \text{ } \mu\text{m}$  long and  $100 \text{ } \mu\text{m}$  wide. Gate-source and drain-source distances were  $1 \text{ } \mu\text{m}$  and  $4 \text{ } \mu\text{m}$ , respectively. All transistors were passivated with Si<sub>x</sub>N<sub>y</sub>.

For DC and RF characterizations, an Agilent 4156C semiconductor parameter analyzer and an Agilent N5230A network analyzer were used, both connected to a Cascade RF probe station. Devices were placed on a Wenesco thermal chuck. This study has been carried out from room temperature (RT) up to  $250^\circ\text{C}$ , every  $50^\circ\text{C}$ , in air atmosphere. For the wafer RF measurements from  $0.25 \text{ GHz}$  to  $20 \text{ GHz}$ , a standard SOLT calibration was performed at RT. The electron channel temperature was derived for each ambient condition from thermal simulations using ANSYS software.

## Results and discussion

Drain current at  $V_{GS} = 0 \text{ V}$  ( $I_{DSS}$ ), extrinsic transconductance ( $g_{m,ext}$ ) and source and drain resistances ( $R_S$  and  $R_D$ ) worsen as external temperature increases, as shown in Fig. 1, mainly due to the reduction in the 2DEG mobility and electron velocity [1,2]. The maximum of  $I_{DSS}$  decreases from  $0.96 \text{ A/mm}$  at RT to  $0.62 \text{ A/mm}$  at  $250^\circ\text{C}$ , while the maximum of  $g_{m,ext}$  is reduced from  $256 \text{ mS/mm}$  to  $155 \text{ mS/mm}$  (see Fig. 1). On the other hand,  $R_S$  and  $R_D$  increase from  $11 \text{ } \Omega$  to  $24 \text{ } \Omega$  and from  $17.5 \text{ } \Omega$  to  $42 \text{ } \Omega$ , respectively, for a drain current  $I_D = 0.2 \text{ A/mm}$ .

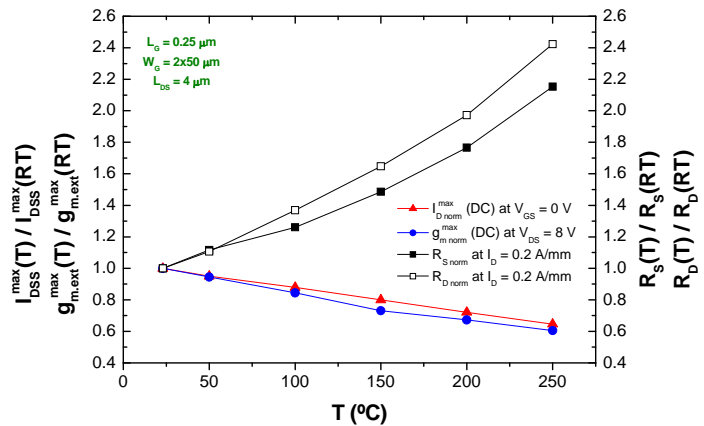
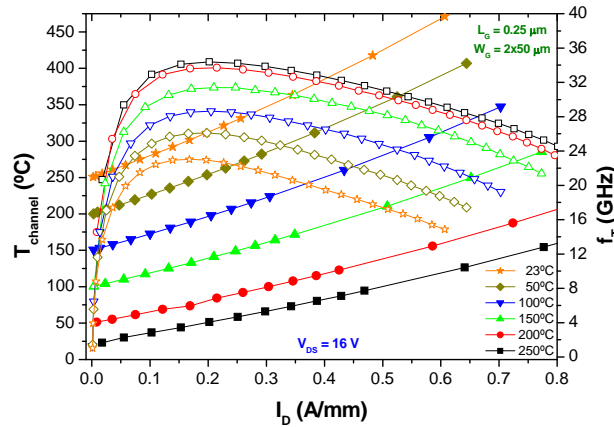


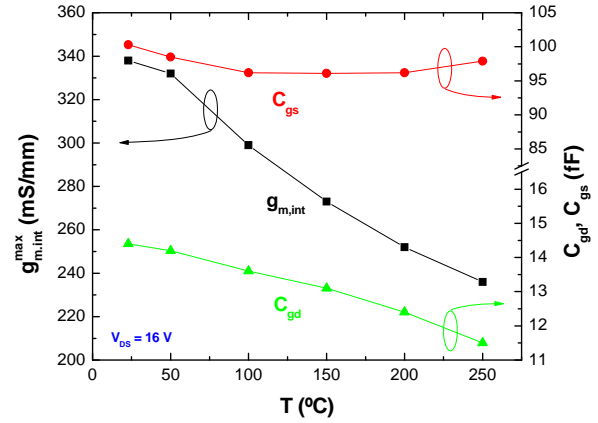
Fig. 1. Normalized values of  $I_{DSS}$ ,  $g_{m,ext}$ ,  $R_S$  and  $R_D$  vs temperature.

Some trapping is present in these devices, since  $I_D$ - $V_{DS}$  characteristics show minor kink effects and the threshold voltage ( $V_{th}$ ) shifts to higher values as devices are heated [3]. In fact,  $V_{th}$  increases almost linearly from -5.15 V at RT to -4.6 V at 250°C, so that  $\alpha(dV_{th}/dT) \cong 2.5$  mV/°C [4].

Concerning device microwave performance, the current-gain cutoff frequency ( $f_T$ ) and the small signal equivalent circuit parameters have been extracted from the measurements of the S-parameters. The maximum of  $f_T$  decreases about 35% from RT (35 GHz) to 250°C (23 GHz), and it seems to be reached at the same  $I_D$  ( $\approx 0.2$  A/mm) for all temperatures, as shown in Fig. 2. In this figure, the estimated temperature of the channel for several drain currents, obtained from the simulations, is also plotted. The increase in the channel temperature at the operation conditions where the maximum of  $f_T$  is achieved is lower than 50°C for all chuck temperatures under test, thanks to the high SiC thermal conductance.



**Fig. 2.** Simulations of channel temperature for drain currents around the maximum of  $f_T$ .



**Fig. 3.** Intrinsic transconductance and capacitances,  $C_{gd}$  and  $C_{gs}$ , as a function of temperature.

HEMT small signal parameters have been calculated as a function of temperature. The intrinsic transconductance ( $g_{m,int}$ ) decreases with temperature from 338 mS/mm at RT to 236 mS/mm at 250°C (see Fig. 3), likely related to a reduction in the effective electron velocity in the channel. Whereas  $C_{gs}$  can be considered constant at different temperatures (see Fig. 3),  $C_{gd}$  suffers a clear decrease as devices are heated, which leads to a decrease in the HEMT global capacitance. This result, together with the shift of  $V_{th}$  to higher values as temperature increases, may be linked with active traps placed in the drain region, where the highest electric fields are reached. From our model, the other intrinsic parameters are almost constant with temperature, except for  $R_{ds}$  which shows an important increase.

## Conclusion

DC and small signal RF characterizations at high temperature have been carried out in AlGaIn/GaN HEMTs on SiC. Transistor performance worsens by 35-40% from RT to 250°C, mainly due to the reductions in mobility and electron velocity. In addition, the presence of traps has also been deduced and linked to the shift in  $V_{th}$  and the variation in capacitances as devices were heated.

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